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EVALUATION OF CATHODIC PROTECTION CRITERIA

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DECEMBER 1979

FINAL REPORT

JULY 1978 - APRIL 1979

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report summarizes the results of a study undertaken to provide an in-depth evaluation of four principal cathodic protection (CP) criteria used for underground and underwater metallic structures. All of the criteria considered make use of structure-to-soil potential measurements. The intent of the report is to provide the background necessary for selecting the proper criterion for a given situation and to remove the misconceptions which often arise. Guidance is provided for correct		

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placement of the reference electrode with respect to the structure being investigated, and for determining how many potential measurements are sufficient. Explanations are given concerning the various voltage (IR) drops which are encountered and instruction is given on how those IR drops are to be considered. A table summary for applying the criteria is given and there is a Bibliography with Abstracts. It must be understood that there are too many variables to allow for general, all-inclusive statements regarding criteria for cathodic protection. Each application must be reviewed individually using the experience from other similar applications together with the information in this report.

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PREFACE

This report was prepared for the Air Force Engineering and Services Center (AFESC), Engineering and Services Laboratory under Job Order Number 21045C01. Report summarizes work done between July 1978 and April 1979 by Harco Corporation, under Phase III of Contract Number F08635-77-C-2048.

The AFESC Technical Monitors were Maj Roger J. Girard and 2Lt Robert J. Gunning. The Harco Principal Investigator was Bernard Husock.

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS), where it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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SECTION I INTRODUCTION

THE PROBLEM

In the practical application of cathodic protection to underground metallic structures, one of the basic concerns is determining whether the applied current and the distribution of that current are adequate for preventing corrosion. Because there is no practical direct method for making this determination, indirect methods have been established for this purpose. These indirect methods have been referred to as "criteria for protection."

This study is concerned with the evaluation of the following four criteria:

- 1 A negative voltage of at least -0.85 volt as measured between the structure and a saturated copper-copper sulfate reference electrode contacting the electrolyte. Determination of this voltage is to be made with the protective current applied. IR drops other than those across the structure-electrolyte boundary shall be considered.

- 2 A negative voltage shift of at least 300 millivolts as measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte. This criterion of voltage shift applies to structures not in contact with dissimilar metals. IR drops other than those across the structure-electrolyte boundary shall be considered.

- 3 A minimum negative (cathodic) polarization voltage shift of 100 millivolts measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte. This polarization voltage shift is to be determined by interrupting the protective current and measuring the polarization decay. When the current is

initially interrupted, an immediate voltage shift will occur. The voltage reading after the immediate shift shall be used as the base reading from which to measure polarization decay.

4 An "instant-off" voltage of at least -0.85 volt as measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte. Determination of this voltage shall be made an instant after the current is interrupted.

The first three of the above listed criteria are given in Section 6 of the National Association of Corrosion Engineers, (NACE) Standard, RP-01-69 (Reference 1). The fourth criterion is one which is in common use for cathodic protection systems for the internal submerged surfaces of steel water storage tanks. In criteria 2 and 3 listed above, the copper-copper sulfate reference electrode is called for even though the voltage change or shift can be determined using other reference electrodes.

It should be understood that these criteria are for steel structures and are not necessarily applicable to Air Force structures constructed of other metals, such as P.O.L. systems with aluminum pipe, or water distribution systems with galvanized steel and copper pipe. In all of the discussion which follows in this report, it must be appreciated that any one of these criteria when put to use in the field cannot be expected to encompass every possible corrosion condition. The selection of any one criterion for field use "attempts...to over-simplify an inherently complex situation" (Reference 2).

The complexity of the problem is recognized in the NACE Standard in the following statement, "no one criterion for evaluating the effectiveness of cathodic protection has proven to be satisfactory for all conditions. Often a combination of criteria is needed for a single structure." In addition, the listing of the criteria as given is, in a sense, merely a

listing of desirable numerical results; there is little or no guidance regarding geometrical considerations such as the placement of the reference electrode and the number of readings to be taken. This report will address itself to the following concerns which are considered basic with respect to the valid field application of the listed criteria:

- 1 Which criterion should be used for a given structure, and what is the basis for its selection?
- 2 Where is the reference electrode placed with respect to the structure?
- 3 How many readings are required to evaluate a particular structure? Related questions involve spacing between readings and how to judge whether a sufficient number has been taken.
- 4 How to consider voltage (IR) drops other than those across the structure electrolyte boundary?

SECTION II

HISTORY - LITERATURE SEARCH

Almost all of the early applications of cathodic protection dating back to Sir Humphry Davy in 1824 were those which used galvanic anodes on submerged metallic structures, such as ship hulls and boilers (Reference 3). Because the effectiveness of corrosion control on these types of structures can be ascertained by visual inspection, there was no particularly compelling need for a criterion for protection. However, when cathodic protection was applied to underground pipelines, the need to establish such a criterion became apparent, because those structures are certainly not readily amenable to physical and visual inspection for the purpose of ascertaining the effectiveness of the cathodic protection.

Mears and Brown (Reference 4) established "a criterion based on equalization of surface potentials, accomplished by polarizing the cathodes until their potentials become equal to the open circuit potentials of the anodes." J.M. Pearson (Reference 5) demonstrated that this criterion is "perfectly sound" regardless of the corrosion mechanism, i.e., whether the structure is corroding under cathodic control, anodic control, or mixed control. Although there is universal agreement concerning the correctness of this criterion, Shrier (Reference 6) shows that it is impractical for use in the field for a number of reasons. "First, the open-circuit potential of the anode varies depending on the environment and cannot be easily determined either by thermodynamic calculation or by experiment. Second, the exchange current density for the anodic reaction is often very small."

Ewing (Reference 7) performed extensive field tests in an attempt to establish the open-circuit potentials. In order to accomplish this, he performed tests which ran for 70 to 80 days on a variety of specimens. He found that this potential varied with different environments. Although Ewing concluded that the methods he used were sound, it is apparent that the procedure is not one which yields field data expeditiously.

Thus, there was a definite need for an uncomplicated technique for determining the effectiveness of cathodic protection on an underground pipeline.

Much of the early work on establishing a criterion evolved from the observation of Evans, et.al. (Reference 8) that when cathodic protection is applied to a ferrous structure, there is a "critical" value of current at which the potential shifts in the anodic direction and corrosion ceases. This is the criterion given in the NACE Standard RP-01-69 calling for "a structure-to-electrolyte voltage at least as negative (cathodic) as that originally established at the beginning of the Tafel segment of the E-log I curve."

Pearson refers to this point as a "discontinuity" in the polarization curve, and in common parlance, this point is referred to as the "break" in the curve. Pearson notes that in a cathodically controlled corrosion reaction, as the protective current is increased "another ion such as hydrogen is discharged rather than the metal ion at the reversal of the anode current discharge. This produces a definite discontinuity in the potential."

Despite the fact that this criterion is listed as one of the acceptable criteria in RP-01-69, there are doubts as to its validity. Pearson shows that there are reservations in using this criterion when the corrosion is under anodic or mixed control, and even where the corrosion is under cathodic control, the discontinuity could be blurred because the anodes

are not all reversed at one value of impressed current. Uhlig (Reference 9) lists this criterion as one of the "doubtful criteria" stating that "discontinuities in slopes of polarization curves have no general relation, as has been sometimes erroneously supposed, to anode or cathode open circuit potentials of the corroding system."

Even if the "break in the curve" criterion were totally acceptable, the techniques required to establish whether a particular structure meets that criterion are cumbersome, and the field work often requires personnel with considerable expertise and training. In addition, this criterion establishes the current required for protection of the structure, and the potential at which that protection is achieved can vary substantially from place to place and structure to structure. It is apparent that a criterion which employs straight forward pipe-to-soil potential measurements would be more easily adapted to field work on underground pipelines.

Kuhn (Reference 10) in 1933 suggested the -0.85 volt to copper-copper sulfate criterion on the basis of empirical evidence derived from his experience on pipelines. Despite the fact that this criterion originated empirically, it has since received a surprising amount of theoretical support. Ewing, in his work cited above, (Reference 7) stated that although the "open-circuit" potential values varied in different environments, in all cases it was less negative than -0.85 volt. Schwerdtfeger and McDorman (Reference 11) set up three series of experiments to determine whether there is any theoretical basis for this criterion. The first series of experiments found that the potential of steel in airfree soils of pH 9 was -0.77 volt to a saturated calomel electrode (this is equivalent to -0.85 volt to copper-copper sulfate). At this point, the potential curve for the standard hydrogen

electrode at atmospheric pressure intersects the potential curve for steel when these curves are plotted on a pH-potential diagram. Therefore, this point was considered to be the protective potential. The second series of experiments indicated that weight loss measurements on steel specimens maintained at the -0.85 volt potential in five corrosive soils confirmed the effectiveness of this value. The third series of experiments attempted to relate the break in the cathodic polarization curve to the -0.85 volt criterion. Despite the fact that others previously cited here have questioned the usefulness of the break in the curve as a valid criterion, these authors report an interesting relationship. They interpreted the break in the curve as indicating the minimum current initially required for cathodic protection. They state that "although the electrode potential corresponding to this current may be considerably less negative than the protective potential, it was found that the potential generally drifted to the critical protective value before appreciable corrosion occurred." The critical protective value referred to in this statement is -0.85 volt.

Although there is considerable reference in the literature to -0.85 volt as a criterion for protection of steel pipe and to its origin, the exact origin of the criterion which requires a 300 millivolt change in potential is obscure. There is no mention of this criterion in Circular 579 issued by the Bureau of Standards in 1957 although Logan (Reference 12) in a paper given in 1953 refers to "lowering the potential -0.3 volt" as if it were a method in common usage at that time. Logan describes his tests in comparing three criteria (i.e., the break in the current potential curve, the 0.3 volt change in potential and the -0.85 volt) and finds that there is no agreement in these criteria insofar as current requirement is concerned. A NACE report issued by

the Committee on Minimum Current Requirements in 1957 (Reference 2) barely alludes to this criterion by making reference to "a pipe potential change (say 200 to 300 millivolts) criterion." On the other hand, Howell in a paper presented in 1951 (Reference 13) and published in 1952 states that "a number of published reports have suggested that protection is achieved when the potential of the line or structure is made more negative to its environment by perhaps 0.25 to 0.35 volt". He further states that "our experience has been that such a potential change of 0.3 volt is adequate, but we suspect that it may actually result in considerable overprotection."

Unlike the -0.85 volt criterion which has considerable underpinning in theory, the 0.3 volt change criterion appears to be empirical and derived strictly from field experience. It would appear that the rationale for its use is best given by Tefankjian (Reference 14) who in referring to the -0.85 volt criterion states that "for bare structures, this criteiron (-0.85 volt) represents a waste of power and can be costly since current requirements are much higher than is necessary to arrest corrosion." He suggests "a negative swing in pipe-soil potentials of 0.25 to 0.30 volt from the initial or unprotected potentials" and indicates that this is applicable to bare pipe "where unprotected potentials are below -0.5 volt." Thus, although the NACE Standard RP-01-69 calls for a "negative voltage shift of at least 300 millivolts," there is far from total agreement that this is indeed the minimum requirement. Shreir states that a "change in potential of 100 -300 millivolts has been called the swing criterion" and indicates that "although rather inexact, this criterion is probably as accurate and useful as any of the others."

Although the criterion used in most field applications of cathodic protection is either the potential of -0.85 volt or the 300 millivolt change in potential, there are several limitations and restraints which must be recognized when using these criteria. Because both of these criteria make use of potential measurements taken with the cathodic protection current applied, all potential measurements taken in this way have two components, namely:

the initial change in potential which is obtained when the cathodic protection system is first energized.

the accumulated shift in potential which results from the continuously applied current over a period of time; this shift is referred to in RP-01-69 as the "negative (cathodic) polarization voltage shift" and is often spoken of in the trade merely as "polarization."

The initial change in potential consists almost entirely of "IR drops." There are really two IR drops to consider, one is within the electrolyte itself (between the pipe surface and the reference electrode), and the second is in the metal (between the point of contact to the metal and the location of the reference electrode). Although RP-01-69 states that "the corrosion engineer shall consider voltage (IR) drops other than those across the structure-electrolyte boundary...", there are no guidelines given concerning exactly how those IR drops are to be considered. In fact, these are sometimes referred to as "IR error" (Reference 15) with the implication that they contribute little or nothing to the protective effect.

Polarization is the voltage shift observed with respect to the original "static" potentials and is attributed to the formation of films on the metal surface resulting from continuously applied cathodic protection current. It is often considered to be a more reliable indicator of the degree and effectiveness of cathodic protection than the other criteria because there is no problem with consideration of IR drops. Despite the acceptance of polarization shift as a measure of cathodic protection effectiveness, there is surprisingly little in the literature concerning its origin or application. The NACE Course No. 2, "Corrosion Prevention by Cathodic Protection," (Reference 16) refers to a "polarization time factor" in the chapter on criteria. The only other reference work found which discusses the accumulated polarization shift with respect to time and its use as a cathodic protection criterion was Ewing's work previously cited (Reference 7) where in his conclusions he states, "the change in potential or polarization necessary for protection of pipelines is probably always less than 0.1 volt." The origin of the value of 100 millivolts is obscure. It has been stated that the NACE committee, which wrote the RP-01-69 Standard, chose that value on the basis of a number of verbal opinions expressed which suggested that because an accumulated polarization of 50 millivolts should be adequate in most cases, 100 millivolts will be more than adequate. In conducting this literature search, no other rationale for the value of 100 millivolts could be found.

The fourth criterion to be evaluated, i.e., an instant-off voltage of at least -0.85 volt to copper sulfate, is not mentioned in any of the literature or reference works reviewed. It appears to be derived from work done in providing cathodic protection for the internal submerged surfaces of steel, water-storage tanks. In obtaining

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potential measurements inside of water storage tanks which have impressed current cathodic protection systems, there are steep voltage gradients within the water when the current is on because of the close proximity between the anodes and the protected surfaces. An instant-off reading avoids the problem with these voltage gradients because there is no current to generate these gradients. It in effect is an -0.85 volt criterion in which the IR drops do not have to be considered because they have been eliminated by turning the current off.

SECTION III

SELECTION OF A CRITERION

When confronted with the problem of selecting a specific criterion for a particular cathodic protection application it must be appreciated that just because there are a number of criteria from which to choose, this does not arbitrarily give us the freedom to select any one of the criteria and to use the criterion which happens to be most convenient. In selecting a criterion, a complete understanding of its meaning is necessary. In order to interpret the results properly, a complete understanding of the restraints and limitations imposed on that criterion is also necessary.

If the results obtained with the particular criterion selected indicate that the level of cathodic protection on the structure does not meet that criterion, we do not have the freedom to capriciously select another criterion which may be more easily met. In choosing a criterion under any circumstance, we must make sure that it be appropriate for the particular application in question.

This section will discuss each of the four criteria in relationship to how they are to be used as well as outline their respective advantages, disadvantages, and limitations. Questions concerning electrode placement, number of readings required, and how to consider the IR drops are regarded to be of such importance in interpreting results, that each of these questions are discussed individually in Sections IV, V, and VI of this report.

It should be noted that cathodic protection when properly applied produces a change in the potential of a structure with respect to a reference electrode placed in the soil in proximity to that structure. The cathodic protection current makes the potential thus measured more negative than the

potential was before the current was applied, and the amount of change produced is a measure of the effectiveness of the cathodic protection at that location.

There are two basic potential changes which are to be considered when cathodic protection is applied as shown in a typical graph of potential v.s. time, Figure 1. When the current is applied at Point A, there is a change in potential at the instant the current is turned on as represented by the line A-B. This potential at B is often referred to as the "instant on" potential. As the current is continuously applied over an extended period of time, the potential continues to increase negatively because of polarization as represented by the line B-C, and the resultant change in potential between B and C is referred to as the "polarization voltage shift." Polarization of a structure is a phenomenon which occurs over a long time period and a structure may not be entirely polarized even after the cathodic protection system has been in continuous operation for many months.

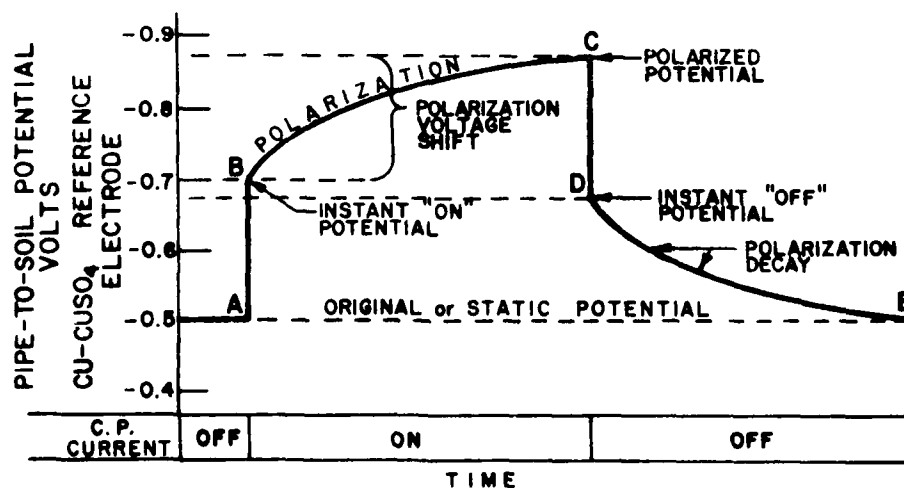


Figure 1 - Pipe-to-Soil Potential versus Time Upon Application of Cathodic Protection (Typical)

If the cathodic protection current is turned off after the structure has polarized, the potential becomes less negative at the instant of turn off as represented by line C-D. It can be seen that the instant "off" potential at point D, is more negative than the original, but that at that point the potential starts to decay or depolarize back to the unprotected original potential at point E.

-0.85 VOLT TO CU-CU SO₄

This criterion is by far the one most often used and the one in which there seems to be the most confidence. Because the potential readings are taken with the current applied and because there is no need to compare existing potential readings with readings taken before cathodic protection was applied, it is apparently also the one most easily adapted for field testing. When testing an impressed current system, there is no need to interrupt the rectifier units. It is particularly useful in a galvanic anode system where disconnecting anodes in order to perform the tests is normally not feasible.

It is also the most appropriate criterion to use in areas of stray DC currents from outside sources. If a pipeline remains at a potential more negative than -0.85 volt, despite fluctuations resulting from stray DC currents, and even when depressed by interference from other cathodic protection systems, that pipeline can be considered as still receiving adequate cathodic protection. Only when the potentials are driven to values less negative than the -0.85 volt level, need there be concern about interference and if the potentials are driven to values less negative than the original static potentials, then the pipe is not only not receiving adequate protection but, in fact, corrosion is being accelerated.

Because the measurements are taken with the cathodic protection current applied, there are voltage drops which are included in the potential measurement but which do not necessarily contribute to the level of cathodic protection. These voltage drops are referred to in RP-01-69 as "voltage (IR) drops other than those across the structure-electrolyte boundary." There are two significant drops, the voltage gradient in the soil and the metal voltage drop in the pipeline resulting from line current. These IR drops will be discussed in greater depth in Section VI of this report.

Because voltage gradients and voltage drops resulting from line currents in the pipeline are often negligible on coated pipelines, the -0.85 volt criterion is well suited for use on coated lines. The IR drops referred to are usually not significant and the original static potentials are often more negative than -0.5 volt. Therefore, a -0.85 volt level is readily obtainable on coated pipe with a reasonable level of cathodic protection current.

However, on bare or poorly coated pipe, a -0.85 volt criterion may not be required and in fact may be excessive and wasteful of cathodic protection current. The excessive requirement imposed by the -0.85 volt criterion is especially true on older bare pipes which have static potentials much less negative than -0.5 volt and sometimes approach -0.3 volt. Parker (Reference 17) in discussing the -0.85 volt criterion noted that "the entire structure is fully protected, of course, only if this criterion is met at every point on the surface." But he then states that "this is not a minimum requirement; it is a maximum. In other words, it is almost certainly true that protection is complete when this change is achieved. It is also possible to have complete freedom from active corrosion at lower potentials."

If this -0.85 volt criterion is used on bare pipelines, there must be an awareness of the IR drop in the soil as well as the IR drop in the pipe (see Section VI); therefore, the position of the reference electrode is of greater significance on bare pipe than on coated pipe (see Section IV).

In cases where other metals are connected to the steel pipeline, the RP-01-69 Standard cautions that the corrosion engineer shall consider "the presence of dissimilar metals." If the metal connected to the steel pipeline is copper, the -0.85 volt criterion would be valid because bringing the potential to that level would certainly indicate that the influence of the copper had been overcome. However, if the other metals are aluminum or galvanized iron, where the original static potential may be more negative than -0.85 volt, it is obvious that the -0.85 volt criterion would not be valid.

In summary, in evaluating the use of the -0.85 volt criterion for cathodic protection, the following statements can be made:

- 1 It is the simplest and most convenient for use in the field.
- 2 It yields results which are apparently the easiest to interpret.
- 3 It is particularly well suited for use on coated pipelines where IR drops in the soil are not significant and where the position of the reference with respect to the pipeline is not critical.
- 4 It is particularly well suited in areas of stray DC currents and where there is interference from other cathodic protection systems.
- 5 It can be excessive for bare or poorly coated pipelines, particularly older lines with low negative static potentials.

- 6 On bare pipelines, the IR drops in the soil and in the metal are an important consideration and the position of the reference electrode with respect to the pipe can be critical.
- 7 It can be used in dissimilar metal structures where the other metal is noble to steel, such as copper, but should not be used where other metals are anodic to steel, such as aluminum or galvanized steel.

300 MILLIVOLT CHANGE IN POTENTIAL

This criterion is not utilized nearly as often as the -0.85 volt criterion, but is probably second in popularity among the various criteria for iron and steel. It is not as convenient for field use because "off" and "on" readings are required. The results obtained are more difficult to evaluate and often require considerable judgement and experience because it is necessary to compare readings after protection with readings before protection. This comparison is often not possible because the original static potentials may be unavailable or because they were never taken.

The statement of this criterion in RP-01-69 is ambiguous and is subject to various interpretations. There is no indication in that document as to whether the change should be measured immediately after a given cathodic protection system is energized or whether a period of time should be permitted to elapse in order to build polarization. It must be recognized that when the 300 millivolt criterion is used on bare pipe (the most frequent application) the immediate change upon energizing the system consists almost entirely of the soil and metallic IR drops. Under some conditions, this immediate change could be 300 millivolts or more. RP-01-69

again indicates that we should consider the "IR drops other than those across the structure-electrolyte boundary" but gives no guidance concerning how to consider them.

One way to resolve the ambiguities in applying this criterion, is to use the total change in potential obtained after the cathodic protection has been in operation for a period of time sufficient to polarize the structure. This total change in potential will include IR drops as well as polarization shift. Because this criterion is used almost exclusively on bare pipe, these IR drops can represent a significant portion of the total change in potential generated by the cathodic protection system. Therefore, the determination of whether or not a total change of 300 millivolts is adequate for preventing corrosion requires considerable experience. It is too formidable a task to attempt to lay down complete guidelines for judging the adequacy of this criterion to cover all possible conditions. But as a general rule, it can be said that in very low resistivity environments, the initial change in potential will probably be relatively small, but that the pipeline polarizes relatively rapidly. On the other hand, in very high resistivity environments, the initial change in potential will probably be relatively large but polarization proceeds slowly. The actual elapsed times involved depend entirely upon the particular case and the currents used for cathodic protection. The balance which exists between the initial change obtained and the amount and rate of polarization depends upon the resistivity of the environment. The separation of the two components, i.e., initial change and polarization, is not always as clear cut as it may seem. In an impressed current system involving only one rectifier unit, the separation is readily apparent. But in a system with multiple rectifier units and certainly in a galvanic anode system with

distributed anodes, this separation is difficult to determine with any degree of precision. In a galvanic anode system, it is possible to compare the potentials taken shortly after the anodes are connected with the original static potentials. Then after some interval of time, the potential measurements are repeated to determine the amount of polarization.

It is obvious that the 300 millivolt change in potential cannot be used in areas of substantial stray DC currents, particularly where these currents produce considerable fluctuations in potential. Certainly a change in potential of 300 millivolts would have little meaning in areas where fluctuations of more than 300 millivolts are being generated by stray DC currents.

There are also problems in using this criterion in situations where dissimilar metals are involved. Where a more noble metal such as copper is connected to a steel pipeline, a change of 300 millivolts could indicate that the adverse effect of the copper had been overcome, but would not be indicative of adequate cathodic protection of the steel. On the other hand, if more active metals, such as aluminum or galvanized steel, are involved, a 300 millivolt change would not only be indicative of cathodic protection on the steel, but would probably indicate adequate protection of the aluminum and galvanized metal as well.

In summary, in evaluating the use of a 300 millivolt change in potential as a criterion for cathodic protection, the following statements can be made:

- 1 It is more difficult to use in the field than the -0.85 volt criterion, but is easier than the other criteria.
- 2 It is more applicable for use on bare pipelines than on coated lines.
- 3 Because of the fact that IR drops both in the metal and the soil are significant on bare pipelines, considerable

experience is required in determining the effectiveness of cathodic protection.

4 The total change in potential consists of two components, i.e., an initial change and a polarization shift which builds over a period of time. In low resistivity environments, the initial change is small, but polarization is relatively large and can occur rapidly. In high resistivity environments, the initial change can be large, but polarization builds slowly.

5 It is not suited for use in areas of stray DC currents.

6 It should not be used in dissimilar metal situations where the other metal is noble to steel, such as copper.

7 If used in dissimilar metal situations where the other metals are active with respect to steel, such as aluminum and galvanized steel, it may be adequate to indicate protection of those other metals as well as the steel.

100 MILLIVOLT POLARIZATION SHIFT

It was noted in the discussion of the 300 millivolt change criterion that one of the components of the total change obtained is the polarization which is built up by the application of current over a period of time. This is the polarization shift. There are two methods for determining this shift. In the first method, the original static potential must be known. After the system has been operating for a period of time sufficient to "polarize the structure," potential measurements are taken with the current instantaneously "off." The potentials taken at the instant of turn off are compared with the original static potentials. A difference between the two of 100 millivolts indicates that the polarization shift is 100 millivolts.

The way in which the criterion is stated in RP-01-69 seems to imply that at the time of testing the original static potentials are not known. Thus, a second method for determining the polarization shift is described in that document. With that method, the cathodic protection current is turned off and the potential is measured after the immediate decrease in potential which occurs at the instant of turn-off. The current remains off and the potential is allowed to decay. If there is a decay of 100 millivolts, it is obvious that there must have been a polarization in that amount.

We can readily appreciate that using either of these methods in the field can be quite cumbersome and time consuming. Therefore, the usefulness of this criterion is almost entirely restricted to relatively uncomplicated impressed current systems. In applications where there are multiple rectifiers, there must be a means of turning off all the rectifiers simultaneously. In a galvanic anode system, it is impractical to take instant-off potential measurements. Some modified procedure might be used in galvanic anode systems if potential measurements can be taken almost immediately after the anodes are installed. After a period of time, the potential measurements are repeated. The second set of potentials are then compared with the first. The difference in potential between these sets of measurements is the result of polarization, although an IR drop component is present in both sets of measurements.

When measurements are taken with the current off, it can be seen that there is no IR drop component and that there is no need to be concerned with the IR drops either in the soil or in the metal. This is the major advantage of using this criterion. It is particularly appropriate to use with rectifier systems on bare pipelines. Judicious use of this

criterion on bare pipelines may make it possible to provide protection with less current than would be the case with the 300 millivolt change criterion. In addition, the 100 millivolt polarization shift criterion is a more definitive indicator of protection in that it relieves the Corrosion Engineer from making judgements concerning how much of the total 300 millivolts change is the result of IR drops and how much is the result of polarization. There is no doubt that the seemingly complicated techniques required in the field have resulted in the under-utilization of this criterion. This criterion can no doubt be used far more extensively than it has been to date, particularly in resolving IR drop problems on bare pipe.

The application of this criterion should probably be limited to bare pipe. There are no apparent special benefits or cost savings resulting from using this criterion on coated pipe instead of the -0.85 volt criterion.

The polarization shift criterion is definitely not one to use in areas of stray DC currents where potentials fluctuate with time.

In dissimilar metal situations, a 100 millivolt polarization shift on all the interconnected metals when more active metals such as aluminum or galvanized steel are connected to steel would be appropriate and would be indicative of protection on the steel and some level of protection on those other metals. In situations where noble metals are connected to the steel, the degree of cathodic protection on the steel would depend on the amount of influence of the copper.

In summary, in evaluating the use of a 100 millivolt polarization shift as a criterion for cathodic protection, the following statements can be made:

- 1 It is difficult to use in the field, especially on galvanic anode systems, and on impressed current systems with multiple rectifier units.
- 2 Time is required for the formation of the polarization films and for ascertaining polarization decay.
- 3 It is more appropriate for use on bare structures although it could be used on coated structures as well.
- 4 It eliminates the problem of considering IR drops.
- 5 It is not appropriate for use in stray current areas.
- 6 It could be applicable in some situations involving dissimilar metals. It would be applicable in situations where steel is connected to active metals, such as aluminum or galvanized metal, but would be less applicable where steel is connected to noble metals, such as copper.

INSTANT-OFF OF -0.85 VOLT

This criterion is similar to the 100 millivolt polarization criterion, except that the required potential level is considerably higher. For this reason, it cannot be considered appropriate for use on bare pipelines. In most instances, not only would very substantial currents be required to meet an instant-off of -0.85 volt criterion, but it is likely that many situations would exist where that degree of polarization would be essentially impossible to attain.

Thus, it would appear that this criterion is most appropriate for use on coated pipelines. It is doubtful whether this degree of protection is always required on coated

lines, but if this level is achieved, there can be no doubt about the adequacy of the cathodic protection. However, if an "off" reading of -0.85 volt is achieved at the least protected locations, there is a possibility that the level of protection at other locations might be excessive. At locations of excessively high negative potential levels, it is possible for the coating to be subjected to potentials capable of causing disbondment. Therefore, when using this criterion, the potentials should be carefully monitored over the entire structure.

The field problems associated with gathering data and performing tests are similar to those associated with the 100 millivolt polarization shift. Interpretation of results is somewhat easier inasmuch as it is not necessary to compare readings taken after protection with readings taken before protection. But there still exist the difficulties in trying to obtain valid instant-off readings in galvanic anode systems or in impressed current systems which have multiple rectifier units. There are also difficulties in obtaining valid readings in areas of stray DC currents and interference; although, if the polarized potential remains more negative than -0.85 volt, the structure would very likely be protected despite the stray current.

In dissimilar metal conditions, this criterion would be valid where steel is connected to copper although the current required to achieve this level of protection could be excessive. Where steel is connected to aluminum or galvanized steel, this would not be an adequate criterion.

In summary, in evaluating this criterion, the following statements can be made:

- 1 Field measurements are easier than those using the 100 millivolt criterion but can still be cumbersome except in uncomplicated impressed current systems.

It is not readily adaptable for use on galvanic anode systems or multiple rectifier systems.

- 2 It eliminates the problem of considering IR drops.
- 3 Results are easier to interpret than those obtained using the 100 millivolt shift criterion.
- 4 It is considered excessive for use on bare pipelines.
- 5 It can be used on coated pipelines but must be used cautiously to avoid excessively high negative potentials.
- 6 It is theoretically applicable in areas of stray DC current and interference although accurate field measurements would be difficult.
- 7 It can be applied in dissimilar metal conditions where steel is connected to copper, but the current requirement is likely to be more than necessary.
- 8 It is not appropriate in dissimilar metal conditions where steel is connected to aluminum or galvanized metal.

SECTION IV

POSITION OF REFERENCE ELECTRODE

POSITION WITH RESPECT TO PIPE

Although the criteria we have discussed require that potential measurements be taken with respect to a reference electrode, there is little said in the NACE Recommended Practice (Reference 2) to indicate the importance of geometric position of the reference electrode with respect to the pipeline being considered.

On coated lines, the exact position of the reference electrode in testing for cathodic protection is not of great importance. Because almost all of the voltage drop is across the coating, the distance in the earth between the pipe and the electrode has little influence on the potential measurement. Although it is good practice to position the reference electrode directly above the pipeline when taking potential measurements along any pipeline, the exact lateral position of the reference electrode is not critically important on a coated line.

On a bare pipeline, however, the geometrical positioning of the reference electrode has a substantial influence on the potential reading as well as significance with respect to what is being seen regarding the corrosion pattern on the pipeline. Husock (Reference 18) has noted that the "R" in the IR drop is governed by the "resistivity of the soil and the distance between the pipe and the reference electrode." Therefore, the lower the resistivity of the soil and the closer the position of the reference electrode, the lower the IR drop. However, there is a basic dilemma in positioning the reference electrode on a bare pipe. In order to minimize the IR drop in the soil, the reference electrode should be as close to the

pipe as possible. On the other hand, the closer the reference electrode is to the pipe, the more localized the measurement and the smaller the area of the pipe which is evaluated. A consideration of many geometrical factors led Scherdtfeger and Denison (Reference 19) to the conclusion that the optimum position for the reference electrode is from four to six diameters away from the pipe and in a "horizontal plane through the center of the pipeline or at least in a plane somewhat below the earth's surface." Without disputing the correctness of this statement, it is clearly not feasible to take measurements in the field in this way.

Therefore, it has been generally agreed to take measurements on a bare line with the reference electrode placed on grade directly above the pipeline. RP-01-69 states that "voltage measurements on pipelines are to be made with the reference electrode located on the electrolyte surface as close as practicable to the pipeline."

Although placement of the reference on the surface of the earth is no doubt the only practical approach for taking measurements, it should be appreciated that there is a soil IR drop between the reference and the pipe. The British Code (Reference 20) alludes to this problem by stating that "it is possible that an appreciable potential gradient in the soil, due to high soil resistivity and/or heavy current density, could affect the structure-electrolyte potential reading. Therefore, the reference electrode should be placed as near as possible to the structure under testing without actually touching it."

This statement seems to imply that in order to test a bare pipeline correctly and to obtain truly valid measurements, it would be necessary to excavate the line and to place the reference electrode right up against the pipe. This approach is not only impractical, but a reference

electrode placed against the pipeline only gives the potential of the local cell; a reading taken in that manner may not be representative of the potentials which exist on the entire pipeline.

There are some texts which suggest using a reference electrode at "remote earth" (Reference 21) as a method for avoiding the soil IR drop problem. Although a potential measurement to a reference electrode placed at remote earth can be useful and is sometimes used by corrosion engineers in certain specific problems, its use on a general basis in testing for the effectiveness of cathodic protection is not recommended. ("Remote earth" is defined here as the position of the reference electrode at a distance from the structure where turning the cathodic protection current off and on results in no perceptible change in potential.) Parker (Reference 22) addresses this problem of remote earth very well. He notes that the mathematics used to derive the attenuation equations makes use of a "mathematical fiction" which assumes "the existence of an 'infinite bus' or a conductor without resistance lying parallel to the line and separated from it by a rather peculiar resistance medium, one which had a definite measurable resistance in one direction, perpendicular to the line, and an infinite resistance in all other directions." Despite the fact that this mathematical theory of current and potential distribution requires the use of a remote electrode, Parker notes that the corrosion mechanism of concern is almost always galvanic cell corrosion. Because this mechanism "is associated with currents and potentials flowing in geometrically small circuits in immediate proximity to the pipe/soil interface...only an electrode in this vicinity could possibly give a true picture."

In actual practice, the problem is not as irreconcilable as stated here. Parker notes that on coated lines remote earth lies within the coating itself and on bare and poorly coated lines, "theoretical distributions seldom hold in any event." He then states "it is a virtual inescapable conclusion that for valid and reliable results, the electrode always should be placed close to the line."

The lateral position of the reference electrode with respect to the pipeline has been discussed by Sudrabin (Reference 23); he notes that although the -0.85 volt criterion has been generally accepted as the protective potential of iron, "the importance of the reference electrode location in relation to the pipe upon the protection received has had no standard acceptance."

In order to establish the effectiveness of cathodic protection on bare pipe, he advocates the following generalizations:

- "1 Long line corrosion currents are controlled when the protective potential (-0.85 volt) is measured to a Cu-Cu SO₄ reference electrode in a remote location. Intermediate and local cell corrosion currents are reduced.
- "2 Long line and intermediate corrosion currents are controlled when the protective potential is measured to a reference electrode placed over the pipeline. Local cell corrosion currents are reduced.
- "3 Long line, intermediate, and local cell corrosion currents are controlled when the protective potential is measured close to the pipe surface."

Although questions about what a reference electrode actually measures or how much of a structure that electrode

"sees," have not been entirely resolved, a rule of thumb often used on a pipeline is that the reference electrode looks at a length of pipe equal to four times the depth of the line at the location of the electrode. (Reference 12) The electrode is said to measure a distorted average of the various potentials which exist along that length of line. The actual value measured is also influenced by soil and metal IR drops as discussed in Section VI.

Thus, the only way we can be absolutely assured that the local cell corrosion activity has been controlled on a bare pipe is to place the reference electrode immediately adjacent to the pipe surface. However, because the closest practical position is on the surface of the ground directly above the pipe, it must be appreciated that there may be some continuing local corrosion activity even when the criterion is met.

Despite the indicated reservations, it is recommended that all pipe-to-soil potential measurements be taken with the reference electrode positioned directly above the pipe. As Shrier (Reference 6) states "even a moderate amount of polarization results in a considerable reduction in the corrosion rate. As a result, any degree of cathodic protection is successful to some extent, and the optimum amount or 'criterion' of cathodic protection is rather subjective."

POSITION WITH RESPECT TO CATHODIC PROTECTION ANODES

In any discussion of reference electrode position, most of the attention is given to the lateral position of that electrode with respect to the pipe. As a result, some important basic considerations with respect to selecting locations for placement of the electrode along the pipes are not sufficiently stressed. It is often assumed that the

person taking field measurements has sufficient knowledge of cathodic protection to realize that the effectiveness should be judged on the basis of potential measurements taken at locations as far removed from the cathodic protection anodes as possible. Thus, in taking measurements on a pipeline which is protected with distributed galvanic anodes, it is clear that the reference electrode should be placed as far removed (both geometrically and electrically) from the anodes as possible. Certainly potential measurements taken to a reference electrode placed adjacent to the anodes should not be used to judge the effectiveness of the protection.

Therefore, in judging the performance of a cathodic protection system, every effort should be made to take potential measurements at locations where the least response to cathodic protection is detected. In order to insure that this procedure is used, it is good practice to install test stations at those locations of least response. In fact, it is worthwhile to delay the installation of test stations until after the initial testing of the cathodic protection system, rather than to try to ascertain the optimum test station locations before the system is installed. It is also good practice to install permanent reference electrodes at the more representative locations to insure that, when readings are repeated to monitor the system, the readings be taken with the reference electrode at the same location as before.

It should be stressed that, when readings are repeated and compared with previous readings, every effort should be made to duplicate exactly the reference electrode locations. While exact duplication may not be essential on coated pipes, it is critical on bare pipes. It is possible to have substantial differences in potential within distances of as little as one foot or less.

EFFECT OF PIPE DEPTH

An item which is often not appreciated or not even considered is the effect of pipe depth on the potential measurement. It has been noted that on bare pipe there is an IR drop in the soil between the reference electrode and the surface of the pipe. This IR drop in the soil is a function of the distance between the reference electrode and the pipe. Although the effect of the lateral position of the reference electrode has been discussed, it should be noted that the distance between pipe and electrode is governed also by pipe depth. When measurements are taken with the reference electrode directly over the pipe, the distance between the electrode and the pipe will vary if the depth of the pipe varies. Therefore, there will be less IR drop in the measurements taken on shallow pipes than in measurements taken on deeper pipes.

Thus, readings which appear to be of lower negative potential in some areas along a bare pipeline may not necessarily be indicative of a lower level of cathodic protection but may be the result of less earth cover at those areas than at others. Similarly, higher negative potential readings in some areas may be merely the result of greater depth and may not be related to the level of cathodic protection.

SECTION V

NUMBER OF READINGS

The problem of determining the number of readings to take on a given structure is often the most perplexing one which confronts the practitioner new to the cathodic protection field. The aim of operating a cathodic protection system on an underground structure is to distribute sufficient protective current to the entire surface area of that structure. However, even if it were possible to take a discrete measurement adjacent to every point on the surface, this obviously would be totally impractical. Therefore, in taking potential measurements for the purpose of testing for the effectiveness of cathodic protection, a sufficient number of appropriately distributed readings to represent the entire structure must be taken. The questions that then arise are:

- 1 How many readings should be taken?
- 2 At what spacing should readings be taken?
- 3 How can it be determined that enough readings have been taken?

HOW MANY READINGS

It is unfortunate that none of the Standard Recommended Practices or the basic literature addresses this question. The probable reason this question is not more fully reviewed is probably because it is very difficult to give generalized guidelines. There are too many variables regarding structure configuration and geometry, as well as the environments which are encountered, to allow any such guidelines to have any real significance. The best approach is to study each structure individually and to determine where readings should be taken; so that a view of the entire structure is obtained rather than

to proceed on the basis of using a pre-determined spacing between readings. For, it must be appreciated that, in fact, there are never enough readings to be totally sure that all of the corrosion activity has been completely arrested.

SPACING BETWEEN READINGS

The conclusion that there are never enough readings has been verified in recent years with the advent of close interval potential profiles, particularly on coated pipelines. With the development of new electronic instrumentation and more easily manageable field equipment and by processing data through computers, it has become practical to take profiles on pipelines which are essentially continuous (Reference 24). These surveys have been able to detect numerous locations where potentials deviate from the normal on lines which were considered to be adequately protected on the basis of potential measurements taken at test stations at approximately one mile intervals. The deviations from normal, which are often referred to as anomalies, have revealed relatively small "holidays" (defects) in the coating where the level of protection falls below the accepted criterion even though there is an adequate potential level on either side as the tester moves along the line. Other concealed problems related to very local soil conditions, shielding, foreign contacts, and interference are often revealed with this type of survey.

This same technique has found application in similar profiles on bare pipelines, but to a far lesser degree. Although the need for a continuous profile on bare pipe has not had the apparent usefulness as has been the case in detecting anomalies on coated pipe, it has proven to be useful on lines which have had unusual problems difficult to detect with the usual type of potential survey.

To date, most of the work using close-interval potential measurements has been on cross-country pipelines. It is very likely that advances in technology and improvements and refinements in procedures will make practical the use of the close-interval survey on underground facilities at airbases and housing developments. Until that time, the decision of how many readings to take will remain largely dependent upon the judgement and experience of the person responsible for testing the structure.

ARE THERE ENOUGH READINGS

How can someone tell whether enough readings have been taken? This question was asked of a number of corrosion engineers. Some of the responses are:

- 1 "One never knows for sure that enough readings have been taken."
- 2 "When I am satisfied that the entire surface of that structure is receiving protective current."
- 3 "That you are 'seeing' the complete structure."
- 4 "I'm not sure you do except with a close-interval potential profile."
- 5 "When the expense of taking additional readings exceeds the benefit."

Perhaps the best response is the last one. In actual applications, it will be necessary to tolerate and accept a degree of uncertainty. However, it must also be realized that unrevealed problems can manifest themselves in leaks in the structure. Therefore, the operational importance of the particular facility will often dictate how detailed the results need be which, in turn, dictate how many readings need to be taken.

SECTION VI
DISCUSSION OF IR DROPS

It has been seen that two of the criteria being evaluated (namely the -0.85 volt referenced to a copper-copper sulfate electrode and the 300 millivolt change in potential) are to be used with the qualification that "the Corrosion Engineer shall consider voltage (IR) drops other than those across the structure-electrolyte boundary for valid interpretation of his voltage measurements." (Reference 1)

The expression "voltage (IR) drops" as used above is not adequately defined in Reference 1. This is unfortunate because the IR drops intended in the above statement are often confused with the IR drops in the measuring circuit itself (i.e., those that result from contact resistance, wire resistance, resistance in the electrode, etc., as shown in Figure 2).

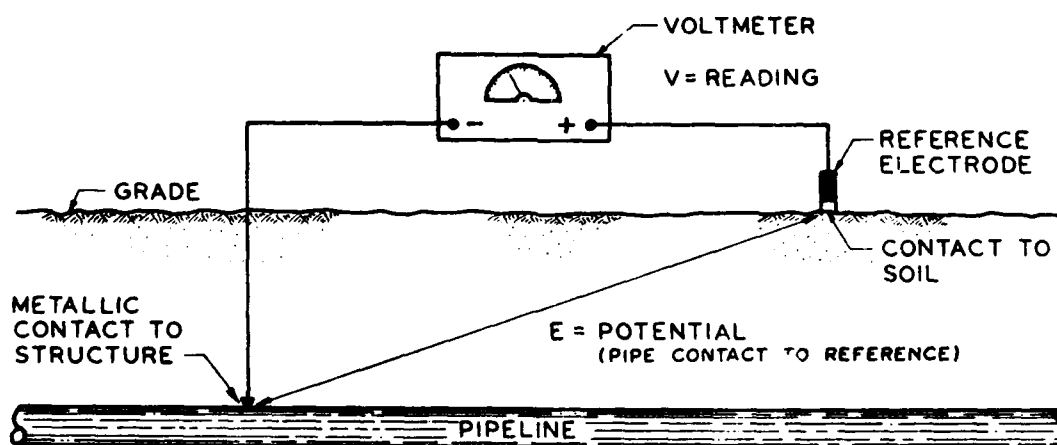


Figure 2 - Circuit for Measuring Pipe-to-Soil Potential

The resistances in the measuring circuit will cause voltage (IR) drops which will make the voltage (V) readings on the voltmeter less than the absolute value of the pipe-to-soil potential (E). However, the IR drops in the measuring circuit are not the ones referred to in the above statement because these IR drops are compensated for by using high resistance instruments or by using a potentiometer-voltmeter. Instrumentation alone or taking the readings "potentiometrically" does not eliminate the IR drops in the value of E itself because these IR drops are an inherent part of the pipe-to-soil potential as measured.

It is the IR drops in the soil (IR)_s and metal of the pipeline (IR)_m that must be considered as shown in Figure 3 and the following equation:

$$E = E_p + (IR)_m + (IR)_s$$

where:

E_p = the pipe-to-soil potential which exists between a hypothetical reference electrode immediately adjacent to the pipe surface and a metallic contact to the pipe close to the reference electrode.

(IR)_s = Voltage (IR) drop in soil between the hypothetical reference electrode placed immediately adjacent to the pipe surface and the actual position of the reference electrode placed at grade (or other location).

(IR)_m = Voltage (IR) drop in pipe (often referred to as metal IR drop) between a point of metallic contact close to the reference electrode and the actual point of contact to the structure.

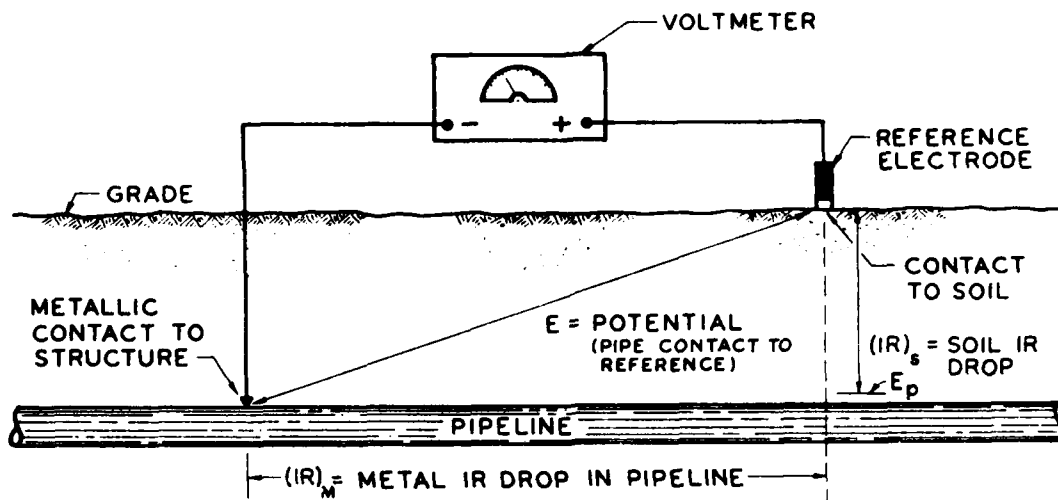


Figure 3 - IR Drop in Pipe-to-Soil Potential

SOIL IR DROP

Soil IR drop in the measurement of pipe-to-soil potential on well coated pipelines is not a problem because almost all of the voltage drop appears across the coating. However, when taking potential measurements on bare pipelines, soil IR drop can be of considerable importance. Unfortunately, its significance is not completely appreciated and there is no complete agreement on exactly how it should be considered. NACE Basic Course No. 2 (Reference 16) refers to the IR drop as "IR-drop error" implying that it is necessary to eliminate it completely in order to obtain a valid pipe-to-soil potential value. On the other hand, Sudrabin (Reference 23) states that "it has been demonstrated in cathodic protection that the cathodic polarization is entitled to an (IR) drop potential gradient through the resistive soil surrounding the pipe."

Because there have been no specific guidelines developed for considering the soil IR drop, the best that can be expected by any corrosion practitioner is to be aware of its significance and to interpret readings on bare pipe accordingly.

For example, in the very low resistivity environments, such as sea water, the effect of soil (in this case, water) IR drop can be entirely ignored. In addition, it can be disregarded in soils of less than 1000 ohm-centimeters and probably neglected even in soils of up to 5000 ohm-centimeters. In fact, in the geographical areas where the -0.85 volt criterion was first used, namely Louisiana and Texas, most of the soils fall in this category of resistivity, and Parker (Reference 17) has noted that the -0.85 volt criterion is based on using a reference at the surface and presumably includes the soil IR drop.

In soils of higher resistivity, the soil IR drop should be determined in order to accurately interpret the potential measurements. In impressed current applications, simply cycling the rectifier off and on and noting the instantaneous difference between the potential measurements should be sufficient to determine the soil IR drop at a given location because the initial voltage shift will include both the soil and the metal IR drop. In cathodic protection systems where it is impractical to turn all of the current off at a given instant, (i.e., systems with multiple rectifier units or galvanic anode systems), this method of determining the soil IR drop may not be possible. Although mathematics for calculating the soil IR drop suggested by Howell (Reference 13) as derived from work done by Kasper (Reference 25) have been described by Sudrabin (Reference 23), the accuracy of

this calculation is limited because it assumes an environment of uniform resistivity, which in turn, assumes uniform current density.

Another method for determining the potential at the pipe surface is one which uses a null bridge circuit. Typical circuits are described by Pearson (Reference 5) and Holler (Reference 26). These circuits have been used for research work by the Bureau of Standards and for other special applications but are not recommended for general field measurements of potential because of the specialized instrumentation required and because of the skills required to perform the tests.

In summary, the soil IR drop is important only on bare pipe and it can be disregarded in many low resistivity soils. Its influence, however, can be significant in higher resistivity soils and should be understood for proper interpretation of potential measurements. In high resistivity soils, it is possible that a potential taken at the surface which appears to meet the criterion may actually translate to an inadequate level of cathodic protection at the pipe surface.

METAL IR DROP

The IR drop which results from line current in the pipeline can never be ignored or disregarded as was the case with the soil IR drop. The metal voltage drop in a pipeline between the point of contact and the location of the reference electrode must always be considered in the interpretation of the potential measurement. It has not received the attention it should probably because, in taking potential measurements, the reference electrode is often placed close to a test station. Where the reference electrode is adjacent to the test station, the metal IR drop is negligible. But as the

reference electrode is moved away from the test station, a metal IR drop component is added to or subtracted from the actual pipe-to-soil potential as shown in Figure 4. If line current flow on the line is from the reference electrode location toward the pipe contact as shown in Figure 4(a), the actual pipe-to-soil potential $E_{p/s}$ will be less negative than the reading on the voltmeter (V) by the amount of voltage drop in the line. Conversely, if the direction of line current is from the contact toward the reference electrode location as shown in Figure 4 (b), $E_{p/s}$ will be more negative than the reading on the voltmeter (V) by the amount of voltage drop in the line.

Thus, any time a reading is taken along the line where the reference electrode is at a distance from the pipe contact, this circumstance must be considered. On pipelines protected with distributed galvanic anodes individually connected to the pipeline, the effect of the line current can be ignored, but on lines protected by impressed current systems, the effect of line current can be substantial. This is particularly true in systems on bare pipes where the applied currents are large.

Because of the metal IR drop, it is good practice on long cross country pipelines to install test stations with means for measuring line current. Thus, if the line current has been determined and the weight of the steel pipe is known, then the voltage drop can be calculated from the following formula (Reference 28):

$$\text{Metal IR Drop} = I \times \frac{0.252}{W}$$

where:

metal IR drop = voltage drop, millivolts per 1000
feet

I = line current, milliamperes

W = weight of steel pipe in
pounds per foot

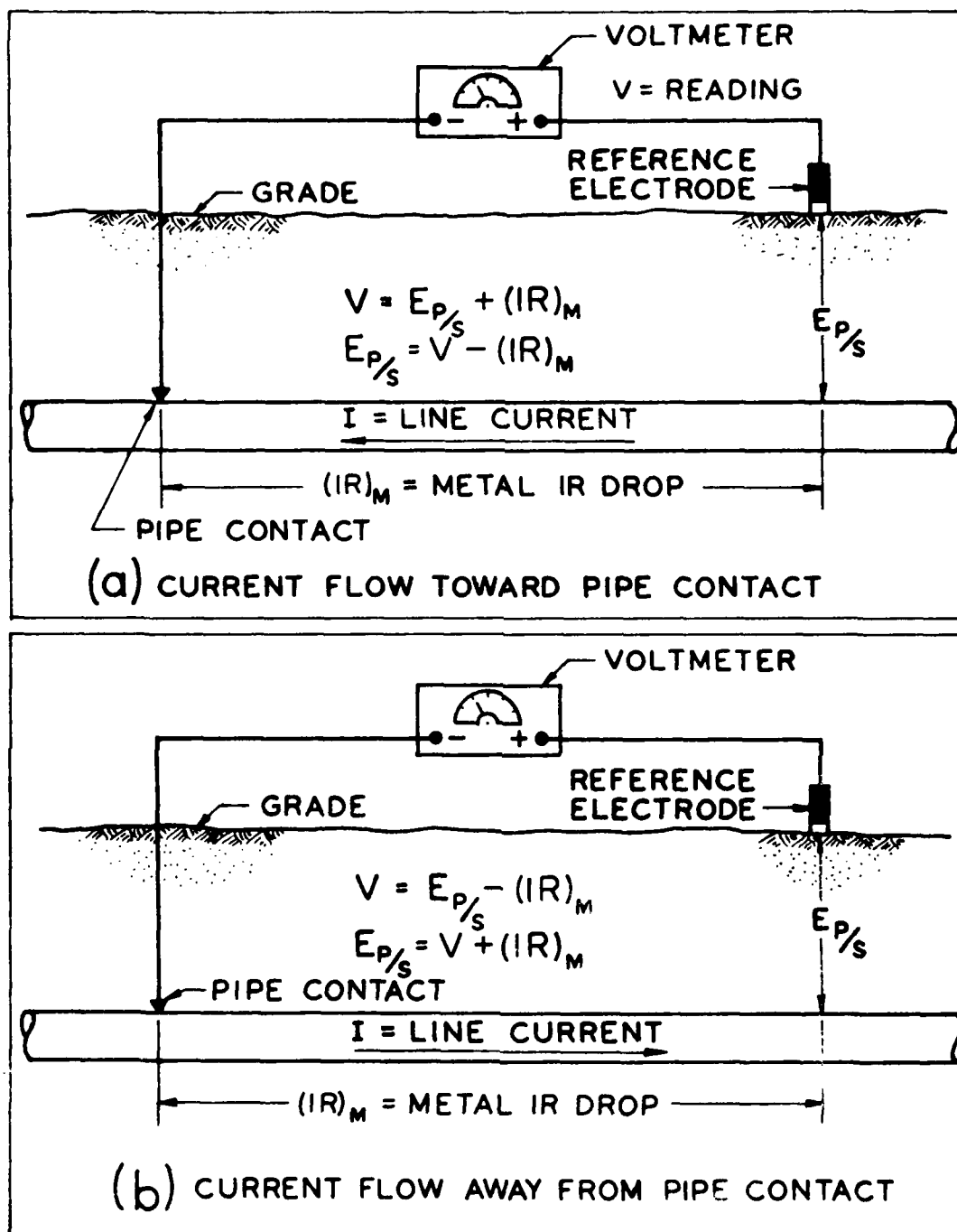


Figure 4 - Effect of Metal IR Drop

In a network of pipelines, the determination of the metal IR drop is not nearly as straightforward as in the case illustrated. There are often multiple metal paths between the location of the reference electrode and the point of pipe contact, and the directions of the current in those paths are random and not amenable to calculation. Therefore, in networks of pipes protected by rectifier units, the following recommendations should be observed to minimize the effects of metal IR drop:

- 1 Place the reference electrode as close to the pipe contact as possible.
- 2 Make pipe contact at locations where the line currents are minimum.
- 3 Whenever the reference electrode is placed at a distance from the pipe contact, try to confirm (or correct) the reading by taking another reading using the same location for the reference electrode but changing the contact point. There must be no insulators in the pipe between the contact points.
- 4 If there is a difference in potential when the pipe contact is changed but the location of the reference electrode is unchanged, that difference is a result of voltage (IR) drop in the pipe unless there are insulators in the pipe. Then the difference would be due to voltage drop in the pipeline and across the insulator.

SECTION VII

CONCLUSIONS

PROTECTION CRITERIA

This report is an evaluation of the following four criteria for underground steel structures:

- 1 A negative voltage of at least -0.85 volt to a copper-copper sulfate reference electrode taken with the protective current applied.
- 2 A negative voltage shift of at least 300 millivolts resulting from the application of the protective current taken with the current applied.
- 3 A negative (cathodic) polarization shift of at least 100 millivolts.
- 4 An instant-off potential relative to a copper-copper sulfate electrode of at least -0.85 volt.

Although the -0.85 volt with the current applied criterion is the most convenient for field use and yields results which are apparently easiest to interpret, it is best suited for use on coated pipes where reference electrode position and soil IR drop are not critical. It is well suited for use in areas of stray DC currents and where there are interference effects from other cathodic protection systems. It is often excessive for use on bare pipelines, and on bare pipelines the effects of IR drops both in the soil and in the metal may be an important consideration. It can be used in dissimilar metal situations where steel is connected to copper but is not valid where aluminum or galvanized metals are connected to steel.

The 300 millivolt negative shift criterion requires a comparison of off and on readings and, therefore, is less convenient for field use making the results more difficult to

interpret. This difficulty results from the fact that the total change in potential includes IR drops as well as polarization effects. This criterion is most often used on bare pipelines. Because IR drops are more significant on bare pipelines, considerable experience is often required in judging the effectiveness of protection as indicated by this criterion. It is not suited for use in areas of stray DC currents. It should not be used in dissimilar metal situations where the steel is connected to copper, although it can be used where steel is connected to aluminum or galvanized metal.

The 100 millivolt polarization criterion eliminates the problems associated with considering IR drops but is less adaptable for field use than the two previously discussed criteria. Although it could be used on coated pipes, it is more appropriate for use on bare pipelines. It is not appropriate for use in areas of stray DC currents. It is applicable in dissimilar metal situation where steel is connected to aluminum or galvanized metal but is not applicable where steel is connected to copper.

The -0.85 volt instant-off criterion is similar to the 100 millivolt polarization shift except that the required current and potential level are greater. Just like the 100 millivolt polarization shift, the use of the -0.85 volt instant-off criterion eliminates the problem of considering IR drops. The field measurements are less cumbersome, and the results are easier to interpret. It is more appropriate for coated pipes. It is excessive for use on bare pipelines. It can be used in areas of stray DC currents or interference. It can be used in dissimilar metal situations where steel is connected to copper but is inappropriate where steel is connected to aluminum or galvanized metal.

POSITION OF REFERENCE ELECTRODE

The position of the reference electrode with respect to the pipe is important, particularly on bare pipelines. It is recommended that all readings be taken with the electrode placed directly over the pipeline at grade. Although the only way to be absolutely sure that all local cell corrosion has been controlled on a bare pipe is to place the reference electrode immediately adjacent to the pipe surface, this is clearly not practical. Therefore, even if the criterion selected has been met, a reference electrode placement at grade leaves open the possibility that some local corrosion may continue to occur. Placement of the reference in judging the effectiveness of protection should be at locations of least negative potential as far removed from cathodic protection anodes as possible. Although remote earth readings are sometimes useful in specific problems, their use on a general basis in testing for cathodic protection effectiveness is not recommended.

When taking readings on cathodically protected bare pipes, the distance between the pipe and the reference electrode can have a significant effect. The greater the distance, the greater the soil IR drop. Thus, as the reference electrode is moved laterally away from the pipe, the potential will become more negative. In addition, even when the reference electrode is placed directly above the pipe, the depth of the pipe can influence the reading; the greater the depth, the more negative the potential.

NUMBER OF READINGS

In determining the effectiveness of a cathodic protection system, it is necessary to take a sufficient number of readings to insure that the current is distributed to the entire surface area of the structure. Because it is

impractical to take a measurement adjacent to every point on the surface, it is necessary to study each structure individually to determine where readings should be taken to obtain a view of that entire structure. Recent developments have made it practical to perform close-interval profiles which produce potential profiles that are essentially continuous. These have been especially useful on coated lines in finding anomalies such as coating "holiday" and problems related to local soil conditions, shielding, foreign contacts, and interference.

IR DROPS

The criteria in which readings are taken with the current applied are used with the qualification that "the Corrosion Engineer shall consider voltage (IR) drops other than those across the structure-electrolyte boundary for valid interpretation of his measurements." The IR drops referred to in that statement include both soil IR drop and metal IR drop. The soil IR drop is the voltage between a hypothetical reference electrode placed immediately adjacent to the pipe surface at the point of interest and the actual reference electrode placement. The metal IR drop is the voltage between the actual point of metal contact to the pipe and a contact adjacent to the location of the reference electrode. Both of these IR drops are an inherent part of the potential which is measured. On coated pipe, soil IR drop is not usually significant, but it can be considerable on bare pipes especially in higher resistivity soils. Metal IR drops, particularly where there is substantial line current, must be considered on all lines, both coated and bare, particularly where there is some distance between the contact point and the reference electrode location.

Table I is a summary of the material presented in this report and is intended only as a general guide for indicating how the cathodic protection criteria are applied. It is not intended as an iron clad statement. If there are any questions concerning any criteria, refer to the appropriate part of this report.

TABLE 1. SUMMARY OF CATHODIC PROTECTION CRITERIA

Characteristics /Criteria*	0.85 Volt	300 Millivolt Polarization Voltage Shift	100 Millivolt Polarization Instant-Off
Frequency of Use	Most Often Used	2nd Most Often Used	Rarely Used
Readings taken with Cathodic Protection Current	ON	OFF and ON then OFF	OFF
Ease of Field Use	Easiest	Somewhat More Difficult	Not Easy
Suitable for Use in Stray Current Areas	Yes	No	No
Must Consider IR Drop	Yes	Yes	No
Primarily Used On	Well Coated Structures	Bare Structures	Well Coated Structures
Can Also Be Used When Interconnected With	Copper	Aluminum or Galvanized Steel	Copper

*All potential values referred to copper-copper sulfate reference electrode.

REFERENCES

- 1 Recommended Practice, "Control of External Corrosion on Underground or Submerged Metallic Piping Systems," Standard RP-01-69, National Association of Corrosion Engineers, Houston, Texas, 1972 Revision.
- 2 NACE Publication 57-15, "Some Observations of Cathodic Protection Criteria," National Association of Corrosion Engineers, Houston, Texas, May 1957. Vol. 13, No. 5, P. 351t-357t.
- 3 Romanoff, M. "Underground Corrosion," Circular 579. National Bureau of Standards, U.S. Department of Commerce, issued April 1957. Page 180.
- 4 Mears, R.B. and Brown, R.H. "A Theory of Cathodic Protection" Transactions of the Electrochemical Society, 1938.
- 5 Pearson, J.M. "Fundamentals of Cathodic Protection" Corrosion Handbook edited by H.H. Uhlig published by John Wiley and Sons, New York 1948, Page 923-924.
- 6 Corrosion, Second Edition 1977 Vol. 2, Edited by L.L. Shreir, published by Newnes-Butterworths, London & Boston, Pages 11:8 & 11:9.
- 7 Ewing, S.P. "Potential Measurements for Determining Cathodic Protection Requirements" Corrosion, National Association of Corrosion Engineers. December 1951, Vol. 7, No. 12, Page 410-418.

- 8 Evans, V.R., Bannister, L.C. and Britton, S.C. "The Velocity of Corrosion from the Electrochemical Standpoint" Proceedings of the Royal Society (London) 1931.
- 9 Uhlig, H.H. Corrosion and Corrosion Control published by John Wiley & Sons, New York, 1963, Page 193-194.
- 10 Kuhn, R.J. "Cathodic Protection of Underground Pipelines from Soil Corrosion," Proceedings American Petroleum Institute 1933.
- 11 Schwerdtfeger, W.J. and McDorman, O.N. "Potentials and Current Requirements for Cathodic Protection of Steels in Soils", Corrosion, National Association of Corrosion Engineers, November 1952, Vol. 8, No. 11, Page 391-399.
- 12 Logan, K.H. "Comparisons of Cathodic Protection Test Methods" Corrosion, National Association of Corrosion Engineers, July 1954, Vol. 10, No. 7, Page 206-211.
- 13 Howell, R.P. "Potential Measurements in Cathodic Protection Designs" Corrosion, National Association of Corrosion Engineers, September 1952, Vol. 8, No. 9 Page 300-304.
- 14 Tefankjian, D.A. "Application of Cathodic Protection" Proceedings of the Appalachian Underground Corrosion Short Course, West Virginia, University, 1975. Pages 131-147.

- 15 Bushman, J.B. and Rizzo, F.E. "IR Drop in Cathodic Protection Measurements" Paper No. HC-20 printed by Harco Corporation, Medina, Ohio. Materials Performance July 1978, Vol. 7, No. 7, Page 9-13.
- 16 NACE Course No. 2 "Corrosion Prevention by Cathodic Protection" Chapter 5, National Association of Corrosion Engineers, Houston, Texas, 1976.
- 17 Parker, M.E., "Pipe Line Corrosion & Cathodic Protection" A Field Manual, 2nd Edition, Gulf Publishing Company, 1962, Page 25.
- 18 Husock, B. "Pipe-to-Soil Potential Measurements and Cathodic Protection of Underground Structures," Materials Performance, National Association of Corrosion Engineers, May 1971, Vol. 10, No. 5, Page 35-38.
- 19 Schwerdtfeger, W.J. and Denison, I.A. "Geometric Factors in Electrical Measurements Relating to Corrosion and Its Prevention", Corrosion, National Association of Corrosion Engineers, October 1955 Vol. 11, No. 10, Page 25-34.
- 20 Code of Practice for Cathodic Protection, CP1021, British Standards Institution, August 1973.
- 21 Peabody, A.W., "Control of Pipeline Corrosion," Chapter 5. National Association of Corrosion Engineers, Fourth Printing, November 1970.

- 22 Parker, M.E. "Current Requirements for Cathodic Protection Pipe Lines," Corrosion, National Association of Corrosion Engineers, April 1955 Vol. 11, No. 4, Page 52-57.

- 23 Sudrabin, L.P. "A Study of Protective Criteria on A Pipe Section in a Uniform Environment", Corrosion, National Association of Corrosion Engineers, February 1956, Vol. 12, No. 2, Page 16-22.

- 24 Harco Corporation Bulletin, C.P.L. Computerized Potential Log.

- 25 Kasper, C., "The Theory of the Potential and the Technical Practice of Electrodeposition", Transactions Electrochemical Society 77, Pages 353-83, 1940.

- 26 Holler, H. D., "Studies on Galvanic Couples," Corrosion, National Association of Corrosion Engineers, February 1951, vol. 7, No. 2, Pgs. 52-68.

- 27 Thresher, N.P. "Line Current Measurement, Proceedings Appalachian Underground Corrosion Short Course, West Virginia University, 1975. Pages 81-85.

APPENDIX A

BIBLIOGRAPHY WITH ABSTRACTS

This Appendix contains abstracts from some of the reference material used in the preparation of this report. These abstracts are to enable the reader of the report to acquire some appreciation of the source material. They are not intended to substitute for that source material and we urge the reader to refer to the original technical papers and text books whenever a more complete understanding of the subject is required. The numerical order in which these abstracts are presented is not related to the order in which the References in the preceeding report are given.

1. CONTROL OF EXTERNAL CORROSION ON UNDERGROUND OR SUBMERGED METALLIC PIPING SYSTEM. NACE Standard RP-01-69. National Association of Corrosion Engineers, Houston, Texas 1972 Revision.

This NACE Standard was prepared by a group of Corrosion Engineers from oil and gas companies, power and communications companies, as well as governmental agencies and consulting firms. The purpose of this standard was to present procedures and practices for achieving effective external corrosion control on buried and submerged metal piping systems. Considerable emphasis is placed on the design, installation, operation, and maintenance of cathodic protection systems. Section 6 is concerned with "Criteria for Cathodic Protection."

"The purpose of this section (Section 6) is to list criteria for cathodic protection which when complied with either separately or collectively will indicate that

adequate cathodic protection of a metallic system in its electrolyte has been achieved."

It states that the "selection of a particular criterion depends, in part, upon past experience with similar structures and environments wherein the criterion has been used successfully." It notes that the recommended criteria have been developed from laboratory work or have been arrived at empirically. It states that it is not intended that the Corrosion Engineer be limited to these criteria if it can be demonstrated that other means are equally effective.

There is the caution that no one criterion has been satisfactory under all conditions and that a combination of criteria may be required. Major emphasis is placed on voltage measurements with respect to a reference electrode placed at the surface as close to the pipeline as possible (pipe-to-soil potential). A warning is given that the Corrosion Engineer "shall consider voltage (IR) drops other than those across the structure-electrolyte boundary, the presence of dissimilar metals, and the influence of other structures for valid interpretation of his voltage measurements."

The document lists five criteria for steel and cast iron structures as follows:

- 1 A negative (cathodic) voltage of at least -0.85 volt as measured between the structure surface and the saturated copper-copper sulfate reference electrode contacting the electrolyte. Determination of this voltage is to be made with a protective current applied.
- 2 A minimum negative (cathodic) voltage shift of 300 millivolts produced by the application of protective current. The voltage shift is measured between the structure surface and the saturated

copper-copper sulfate reference electrode contacting the electrolyte. This criterion of voltage shift applies to structures not in contact with dissimilar metals.

- 3 A minimum negative (cathodic) polarization voltage shift of 100 millivolts measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte. This polarization shift is to be determined by interrupting the protective current and measuring the polarization decay. When the current is initially interrupted, an immediate voltage shift will occur. The voltage reading after the immediate shift shall be used as the base reading in which to measure polarization decay.
- 4 A structure-to-electrolyte voltage at least as negative (cathodic) as originally established at the beginning of the Tafel segment of the E-log I curve. This structure-to-electrolyte voltage shall be measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte at the same location where voltage measurements were taken to obtain the E-log I curve.
- 5 A net protective current from the electrolyte into the structure surface as measured by an earth-current technique applied at predetermined current discharge (anodic) points on the structure.

2. SOME OBSERVATIONS OF CATHODIC PROTECTION POTENTIAL CRITERIA. Corrosion National Association of Corrosion Engineers, Houston, Texas, May 1957. Vol. 13, No. 5, Page 351t-357t.

Experimental work which attempts to clarify the role of reference electrode location when taking measurements to determine cathodic protection criteria is described. It notes that "experience has not yet yielded a specification for a potential measurement technique whereby the observation of this protective potential value will be assurance that the optimum protective condition exists."

It attributes the lack of an accepted potential measuring technique to many factors affecting the potential "seen" by the reference electrodes. It then describes the experiment which was set up to simulate localized pitting. It notes that localized pitting "is usually the most damaging form of metal destruction observed on pipelines."

There are no clear cut results and conclusions given which can be directly translatable for use in the field. The publication does indicate that IR drop is of lesser importance in lower resistivity environments and that the location of the reference electrode becomes more important as the environment resistivity increases.

3. UNDERGROUND CORROSION. Melvin Romanoff, National Bureau of Standard Circular 579, issued April 1957.

This Circular is a 227-page report on studies of underground corrosion performed by the National Bureau of Standards between 1910 and 1955. The Circular describes the results obtained in field tests of more than 36,500 specimens representing 333 varieties of ferrous and nonferrous materials

exposed in 128 test locations throughout the United States. There is a substantial amount of data with respect to soil types and characteristics. The theory and mechanism of underground corrosion are discussed and the types of corrosion encountered are described. The results of field and laboratory studies are given. The influence of stray DC currents is discussed, and electrical measurements for field use are given.

Chapter 23 is concerned with cathodic protection, and most of that chapter is concerned with criteria and requirements for cathodic protection. Particular emphasis is given to interpretation of potential measurements and cathodic polarization curves. Laboratory and field work which substantiates the -0.85 volt criterion is described. It notes that "when using a potential criterion for cathodic protection on underground pipelines, particularly on bare lines, the positioning of the reference electrode must be considered because the IR drop through the soil resulting from the applied current has a major effect on the potential reading." Varying practices used by utility companies at that time are noted indicating that some companies placed the reference directly over the line and others from 5 to 400 feet away. It then describes work by Schwerdtfeger and Denison (Abstract No. 13) and Sudrabin (Abstract No. 18) but makes no specific recommendations.

A detailed description is given for null circuits developed by Pearson and by Holler for measurement of protective cathodic protection current. These special circuits are designed to eliminate IR drop in potential measurements. In soils having resistivities of less than 1000 ohm-centimeters, the breaks in the curve can be observed without the use of these special null circuits.

4. FUNDAMENTALS OF CATHODIC PROTECTION. J.M. Pearson, Corrosion Handbook by H.H. Uhlig, published by John Wiley & Sons, New York, Page 923, 1948.

This article provides the background necessary for relating the various criteria for cathodic protection to particular corrosion mechanisms. It indicates that it is necessary to know whether the corrosion is under anodic or cathodic control. For either type of control, complete protection occurs when the anode currents reach zero. Therefore, the criterion in which "the polarization of the anodes to the open-circuit potential of the cathodes" occurs, is considered to be perfectly sound in both cases.

Criteria for protection of cathodically-controlled specimens, criteria for protection of anodically-controlled specimens, and those for protection of specimens under mixed control are discussed. Particular emphasis is placed on measurements which determine the "potential discontinuities" in polarization curves. On a specimen corroding under cathodic control, such a discontinuity is indicative of cathodic protection and can occur without any substantial change in half-cell potential. Under anodic control, the determination of completeness of cathodic protection is not so easily obtained, and under mixed control, the placement of the reference electrode with respect to the distance from the anodes or cathodes is important. An inference can be drawn that the criterion which uses the "break in the polarization curve" applies only to corrosion mechanisms under cathodic control.

The criteria suggested in this paper are not specific. Information concerning the type of control which governs the corrosion is necessary in using the relationships indicated. Because of this, these criteria are not entirely practical for

widespread use in underground pipeline work. However, the information in this article is useful in making the corrosion engineer aware that different corrosion mechanisms are at work and that these may require different criteria.

5. CORROSION, Vol. 2, Corrosion Control. L.L. Shreir. Published by Newnes-Butterworths, London-Boston, Second Edition, Pages 11:8 and 11:9, 1977.

In addressing the problem of protection criteria, the author here points out that in a normal corrosion cell, the corrosion rate decreases continually as the cathodic polarization increases and that even a moderate amount of polarization results in a considerable reduction in corrosion rate. Therefore, he states that any degree of cathodic protection is successful to some extent but that the optimum amount or "criterion" is subjective. He agrees with other observers that ideally corrosion is reduced to a zero rate when polarization of the cathodes is equal to the open-circuit potential of the anodes. The impracticality of this criterion is then pointed out because it varies depending on the environment and it cannot easily be determined either by calculation or by experiment. He also points out that the corrosion rate in many instances may be made sufficiently low for most practical purposes even though complete polarization up to the open-circuit potential of the anode has not been achieved.

It is noted that the customary criterion of -0.85 volt reference to copper sulfate is usually sufficiently negative to reduce the corrosion rate below a negligible level in most situations even though the exact open-circuit potential cannot be determined and, therefore, assure "absolute protection." Because of this uncertainty, the author indicates that no

particular potential value has emerged as superior for all applications. He indicates that -0.95 volt is normally used when the environment contains sulfate-reducing bacteria. There is then some discussion about what is referred to as the "swing criterion" or a change in potential of 100 to 300 millivolts and an indication that although this is a rather inexact criterion, it is "probably as accurate and useful as any other so far described."

The author then discusses what he calls the "anodic Tafel constant," which is the polarization required to cause a factor of 10 reduction in the corrosion rate. This constant can be used to predict the polarization necessary to reduce the corrosion by any desired amount.

6. POTENTIAL MEASUREMENTS FOR DETERMINING CATHODIC PROTECTION REQUIREMENTS. S.P. Ewing. Corrosion, December 1951, Vol. 7, No. 12, Page 410.

This paper describes extensive testing work done in attempting to establish what the author refers to as the "open-circuit potentials" required to prevent corrosion. In these experiments, identical groups of six pipe samples were each exposed in four different environments. In each group, current was applied to five of the six samples. The currents were selected to maintain certain designated potentials; one of the samples was used as a control. The tests were run for 70 to 80 days and the corrosion weight losses on the test specimens were correlated with the current and potential measurements taken during that test. The author states that the open-circuit potential measurements were made by placing the reference electrode in contact with the soil directly over the specimen, and he describes a procedure for eliminating the error caused by the IR drop. The description of the method he

used is somewhat complicated, but it appears that the IR drop was eliminated by interrupting the current.

The author found that the potential required to stop corrosion varied with different environments but that in all cases was less negative than -0.85 to copper-copper sulfate by amounts of 0.05 to 0.15 volt. The author also concluded that corrosion was arrested at a value of polarization of less than 0.1 volt. He points out that the circuitry used was not capable of automatic control to hold the potentials reasonably constant. He expresses the opinion that if more precise results were possible, they would probably show that even less polarization and a less negative potential will give complete protection. It would be interesting to repeat the author's work using today's automatic circuits to control potential.

In the discussion to this paper, the author points out that the value of -0.85 volt to copper-copper sulfate will always be adequate for protection in all soils and natural waters assuming that the potential is a true potential and that it does not include any IR drop. He further states that the experiments show that it is not always necessary to maintain a value of -0.85 volt.

7. CORROSION AND CORROSION CONTROL. H.H. Uhlig. Text Book published by John Wiley and Sons, New York 1963, Pages 193, 194.

The measurement of the potential of a protective structure is considered of great importance in practice and is the criterion generally accepted and used by Corrosion Engineers. The criterion is based on the concept "that cathodic protection is just complete when the structure is polarized to the open-circuit anode potential of local action cells." The protective potential for steel is equal to -0.85

volt versus copper-copper sulfate or -0.53 volt on the standard-hydrogen scale.

The theoretical open-circuit potential for iron is calculated using the Nernst Equation. The oxidation potential so calculated is -0.59 volt on the standard hydrogen scale, equivalent to a potential difference of 0.91 volt versus saturated Cu-CuSO₄.

There is a section entitled "Doubtful Criteria" in which it is indicated that "polarizing a steel structure 0.3 volt more active than the corrosion potential is not exact and can lead to under or over protection." The criterion which calls for a break in the E-log I curve is also listed as doubtful because it argues that discontinuities in that curve have no relationship to anode or cathodic open-circuit potentials of the corroding system.

There is a discussion about the position of the reference electrode indicating the ideal position is as close to the structure as possible to avoid IR drop through the soil but suggesting that a compromise position directly over the pipe is acceptable "because cathodic protection currents flow mostly to the lowest surface and are minimum to the upper surface of a pipe buried a few feet below the soil surface." There is a discussion concerning the placement of the reference electrode at a remote position which indicates that the potential measured at that location would tend to be more active than the true potential, and the result would be that the structure may be underprotected.

8. POTENTIAL AND CURRENT REQUIREMENTS FOR CATHODIC PROTECTION OF STEEL IN SOILS. W.J. Schwerdtfeger, O.N. McDorman. Corrosion, November 1951. Vol. 10, No. 7, Page 206.

This paper makes note of the fact that the criterion of -0.85 volt referred to a copper-copper sulfate reference electrode is based on experience as first proposed by R.J. Kuhn. It also notes that although this criterion has been used successfully on underground structures, there was as yet (prior to publication of this report) no theoretical or experimental basis for this criterion applicable to all soils and environments. It further notes that the measurements are taken with the current applied and there is, therefore, an "indefinite IR drop between the reference electrodes and the electrical boundary of the corrosion circuits." In order to establish a basis for the -0.85 volt criterion, a number of experiments were set up.

In the first series of experiments, the potentials of steel electrodes were measured in 20 air-free soils ranging in pH from 2.9 to 9.6 and in resistivity from 60 to 17,800 ohm-cm. These experiments found that the potential of steel in air-free soil, which has a pH 9, was -0.77 volt referenced to a calomel electrode. Because corrosion in an air-free soil at pH 9 is considered to be negligible, this value was considered to be equivalent to a protective potential. The value of -0.77 volt to a calomel electrode is equivalent to 0.85 volt to a copper-copper sulfate electrode.

In the next series of experiments, weight-loss measurements were taken on steel samples in five severely corrosive soils obtained from the National Bureau of Standards soil corrosion test sites. Weight losses on all samples at -0.77 volt to calomel were small compared to the weight losses of the controls. Therefore, this potential was considered to be the "approximate optimum protective potential."

A third series of experiments were conducted in which the current required for cathodic protection was determined by finding breaks in the cathodic polarization curves. This value of current was interpreted to be the minimum current initially required for cathodic protection. Although the initial electrode potential corresponding to that current was considerably less negative than the -0.77 volt, it was found that the potential generally drifted up to that value when the current as indicated by the break in the curve was maintained.

In summary, this paper describes the considerable work which was done by the Bureau of Standards in establishing a theoretical and experimental basis for the -0.85 volt criterion. The results obtained make a very strong case for that criterion. In the discussion of this paper, in response to the question "Where would you say that pipe-to-soil potential measurements should be made?", the statement was made "for the protected potential to have significance, all of the IR drop external to the electrical boundary of the corrosion circuit must be excluded."

9. COMPARISONS OF CATHODIC PROTECTION TEST METHODS. K.H. Logan. Corrosion, July 1954, Vol. 10, No. 7, Page 206.

This paper is an attempt to compare the various criteria for cathodic protection of pipes laid in soils having a wide range of resistivities and other characteristics. Results obtained by using the break in the current potential curve are compared with the potentials of 0.3 volt change and -0.85 volt to copper-copper sulfate. Various procedures were used which both included and excluded the IR drop and used a reference electrode both over the pipe and remote from the pipe.

Particular emphasis is placed in this paper on the use of the current-potential curves, and it appears that the author

favours the criterion which uses the break in this curve. He describes procedures for obtaining the curves and indicates that a distinct break was found in all the soils if the IR drop is eliminated. However, he indicates that similar results can also be obtained without eliminating the IR drop, although the breaks are not so clearly defined. In doing these polarization tests, the author recommends that equal-current increments should be used, and although equally spaced time intervals are desirable, they are not always necessary. He further indicates that data can be plotted on rectangular co-ordinate paper as well as semi-log paper although it seems that the vogue today is to use the semi-log paper.

In this work, the author shows considerable disagreement between the criteria investigated, i.e., break in the curve, change in pipe potential of 0.3 volt, and a pipe potential of -0.85 volt to copper-copper sulfate. There is some confusion as to how and whether the IR drop was considered or compensated for in the comparisons of the criteria. But even if it is assumed that the compensation for the IR drop was consistent throughout the author's work, there is no reason for agreement between these criteria even though the author seems surprised by the disagreement and recommends that the reason for the disagreement should be investigated.

As a point of interest, the author refers to work by Pearson with respect to the length of pipe which effects the reading taken by a reference electrode. Pearson's work indicates that the length of pipe is "roughly 4 times the distance between the electrode and the pipe." If this is indeed the case, it is noted that the electrode over a pipe with 3 feet of cover observes the average potential of roughly 12 feet of that pipe.

10. POTENTIAL MEASUREMENTS IN CATHODIC PROTECTION DESIGN.

R.P. Howell. Corrosion, Sept.1951, Vol. 8, No. 9, Page 300.

Because the pipe is buried and cannot be observed directly, the corrosion worker is confronted with the problem of devising measurements which would enable him to determine whether cathodic protection is effective. "These should be simple measurements of potential, if possible, rather than more complex testing techniques." A number of criteria are suggested including measurements for current density, potential change, and current-potential curves as well as straightforward potential measurements. The current-potential curves are considered to be too time consuming and difficult, and the criterion requiring a potential change is considered to be difficult to interpret because the measurements can be obscured by polarization effects. A potential of -0.85 volt to copper sulfate is considered to be acceptable and the statement is made that "it is customary to neglect the IR drop through the soil even though a slight error may result." It is suggested that, on poorly coated and bare pipe, it would be worthwhile to check surface potential gradients so as to estimate the current density at the pipe's surface. A formula is given for calculating the current density.

It is suggested that regardless of the copper sulfate potential, if this calculation indicates a current pickup of 1.0 milliamperes per square foot or more in soil, we can assume that the protection is adequate. A number of examples are given for using cathodic protection on pipelines in salt water with the problems which result from polarization effects. There is the indication that although there may be difficulties in evaluating potential measurements as they relate to the effectiveness of protection, it is sometimes worthwhile to overprotect certain lines in seawater because they are subject to greater corrosion activity than those in soil.

11. CORROSION PREVENTION BY CATHODIC PROTECTION. National Association of Corrosion Engineers, Course Number 2. 1976.

Chapter 5 of this course is concerned with current requirements and criteria of cathodic protection. A number of criteria are given including the use of history and corrosion test coupons as well as potential measurements, potential shift, $E\text{-log } I$, net current flow to the structure. The three most common criteria are potential, potential shift, and $E\text{-log } I$. Included in potential shift in this context is the change in potential as well as the polarization shift. Cathodic protection requires that the cathodic reaction of the structure be polarized to the static potential of the local-action anodes. A typical range for steel in normal environments is -600 to -800 millivolts to copper sulfate; therefore, the -850 millivolts should be adequate in most cases. Although it is possible that there may be unusual cases where the static potential is more negative than this value, the potential criterion usually makes for overprotection because a single selective potential is used to satisfy the worst case.

In using the 300-millivolt change in potential, it is assumed that the difference in potential between the local anodes and cathodes is not more than 300 millivolts. This criterion can be invalid in cases in anodic control.

The polarization shift is related to a time factor and is often a less conservative criterion than the potential criterion of -0.85 volt. The value used as the criterion may be below protection in anodic-control cases.

The basis of the $E\text{-log } I$ criterion is the idea that a potential measured on a structure is a composite of all the reactions. When corrosion is occurring, the potential is a mixture of both anodic and cathodic reactions; as cathodic

protection is applied, the structure becomes more cathodic and less anodic. When cathodic protection is complete, only a cathodic reaction occurs, and a slope change occurs in the E-log I plot. Care is suggested in determining these plots.

12. IR DROP IN CATHODIC PROTECTION MEASUREMENTS. J.B. Bushman, F.E. Rizzo. Materials Performance, July 1978, Vol. 7, No. 7, Page 9.

IR drop is important in cathodic protection measurements and it is often ignored or misunderstood. There is IR drop in the metal as well as IR drop in the electrolyte. A method for calculating the metal IR drop is given and the following table is presented for typical values of metal IR drop.

Various methods for considering the IR drop in the electrolyte are discussed. These methods include:

- 1 Ignore
- 2 Remote earth
- 3 Extrapolation
- 4 Interruption

These methods are in addition to those that use a null-bridge technique. It is noted that, whenever possible, the best possible IR drop correction results from current interruption. Thus, instant-off readings are the best for use whenever IR-drop correction is required.

Summary of IR Drop Correction Techniques

Method	Procedure	Advantage	Disadvantage
Ignore	None	Easy	Incorrect if IR drop is significant
Remote earth	Measure far from protected structure	Apparently easy	Protection criterion must change with situation
Extrapolation	1. Measure EMF variation with position 2. Extrapolate to zero distance	Better correction	1. Time consuming 2. Extrapolation equation
Interruption	Interrupt current at moment of measurement of potential	Best correction	1. Current interruption can be inconvenient 2. Equipment required for rapid interruption

13. GEOMETRIC FACTORS IN ELECTRICAL MEASUREMENTS RELATING TO CORROSION AND ITS PREVENTION. W.J. Schwerdtfeger, I.A. Denison. Corrosion, October 1955, Vol. 11, No. 10, Page 25.

Experiments were conducted to show the relationship between the potential pattern and geometry on metal cylinders in an electrolyte when corroding normally as well as when corrosion is stopped by cathodic protection. It was hoped that the information obtained could be applied to measurements of potentials on subsurface structures such as pipelines.

In Paragraph 4.3 of this paper, it is noted that although pipe-to-soil potential is the chief criterion for evaluating the adequacy of cathodic protection, "the positioning of the reference electrode ought to be done more discriminately." It notes that the practice of the day places the reference electrode at "varying distances from the lines, some placing it directly over the lines and others from 5 to 400 feet away." A major attempt of the work is to define the "electrical boundary" for these measurements with the apparent understanding that measurements taken within the boundary would require an increase in external current and those taken outside the boundary, a reduction in current. The determination of this boundary indicates that when making potential measurements on bare pipe for the application of protective potential criteria for cathodic protection, "it is recommended that the reference electrode be placed four to six pipe diameters from the line, at some distance below the earth's surface and preferably in an approximately horizontal position with respect to the pipeline."

14. CODE OF PRACTICE FOR CATHODIC PROTECTION, CP 1021,
British Standards Institution, August 1973.

This is a 103 page document which discusses in considerable detail the application of cathodic protection to a wide variety of structures including underground structures. Substantial information is given on the design and installation of cathodic protection systems as well as the procedures involved in testing, operating and maintaining those systems.

Cathodic protection criteria are discussed in Paragraph 2.3.2. The criteria for iron and steel with respect to copper-copper sulfate are -0.85 volt in an aerobic environment and -0.95 volt in an anaerobic environment. Although the equivalent potential values with respect to other reference electrodes are given, no other criteria are given. There is a note in this paragraph concerning the protection of steel in concrete. There is no guidance with respect to how the measurements should be taken.

Later in this document under Paragraph 9.3.2.2 "Placing of Reference Electrode," there is a discussion concerning how to take these potential measurements. The major concern seems to be with respect to instrumentation and the obtaining of accurate readings. About the use of those readings regarding criteria for protection, the following statement is made:

"It is possible that an appreciable potential gradient in the soil, due to high soil resistivity and/or heavy current density, could affect the structure/electrolyte potential reading. Therefore, the reference electrode should be placed as near as possible to the structure under testing without actually touching it. However, when the cathodic protection has been applied to a well-coated steel pipeline, the reference electrode may be placed in contact with the soil directly above the structure under test."

15. CURRENT REQUIREMENTS FOR CATHODIC PROTECTION. M.E. Parker. Corrosion, April 1955, Vol. 11, No. 4, Page 52.

Although this paper is primarily concerned with methods and procedures for determining current requirements and designs of cathodic protection systems, it includes, near the end, a very good discussion concerning where to place the reference electrode. The author presents the dilemma that, in order to satisfy the mathematical theory of current and potential distribution, a remote electrode must be used, but in order to determine whether a given section of the line is under cathodic protection, a close electrode must be used. It is then pointed out that the dilemma can be resolved on coated lines in that electrode placement is not critical because a large percentage of the total resistance to remote earth lies within the coating itself. However, he states that on bare lines, "the electrodes always should be placed close to the line" for valid and reliable results.

It is further noted in using both the -0.85-volt criterion and the shift of 0.3 volt that these are based on the use of a near electrode. The term "near electrode" here means one placed directly over the pipe. The author indicates that from a theoretical point of view, it would be desirable to place the electrode even closer, i.e., "immediately adjacent to the pipe/soil interface." However, not only would placing the electrode closer be laborious, there is the objection that the reading obtained might be too-highly localized. It is then indicated that empirical criterion of -0.85 volt is actually based on the experience which presumes that the electrode is placed at the surface directly over the pipe.

The author falls back on experience which has yielded "total cessation of leaks" as an argument in favor of using

the -0.85 volt criterion with respect to a reference electrode placed on the surface of the soil directly over the pipeline. He further gives some good advice on cathodic protection measurements in general. He indicates that all pipe-to-soil potential measurements must be made consistently, particularly with respect to electrode placement. A decision in regard to the criterion can then be made only after all the data are analyzed.

16. PIPELINE CORROSION AND CATHODIC PROTECTION. M.E. Parker. A Field Manual, Second Edition, Gulf Publishing Company, Houston, Texas 1962.

This is a 145 page text (plus appendices) which discusses the measurements and techniques used to survey underground pipelines. It also has information useful for designs of both impressed current, etc. There are four appendices as follows:

- A Fundamentals of Underground Corrosion
- B Basic Principles of Cathodic Protection
- C Table of Properties of Metals
- D Attenuation Equations

On Pages 24 and 25, there is a discussion of pipe-to-soil potential as a criterion of cathodic protection which indicates that it is almost universally accepted that a steel structure under cathodic protection is fully protected if the potential is at least 0.85 volt negative referred to a copper-copper sulfate electrode placed in the electrolyte immediately over the line. It can be shown that for a well coated line, this is as good as next to the pipe. For a bare line, this is not true. It then notes that "bare lines are rarely fully protected in any event." That may have been the case which existed at the time of publication of this book, but it is certainly not the case today.

It is customary and safe to consider a coated line to be fully protected if a survey along its length yields a reasonably smooth potential curve which does not dip below the value of -0.85 volt.

17. PIPE-TO-SOIL POTENTIAL MEASUREMENTS AND CATHODIC PROTECTION OF UNDERGROUND STRUCTURES. B. Husock. Materials Performance, May 1971, Vol. 10, No. 5, Page 35.

In applying the criterion given in RP-01-69, a number of questions arise as follows:

- 1 Which criterion or criteria are applicable to a particular corrosion mechanism?
- 2 Where should the reference electrode be placed to obtain valid readings?
- 3 How many readings are required to obtain an accurate representation of the entire pipeline or piping network?

It is not possible to always provide definite answers to these questions.

To determine which criterion is applicable, some of the questions which must be answered are as follows:

- 1 Are their neighboring sources of stray current which can influence the measurements?
- 2 Is the iron or steel coupled to other metals?
- 3 If the iron or steel is coupled, what is the metal to which it is coupled?
- 4 Is the pipeline bare or coated?
- 5 Is the coating organic or concrete?
- 6 What is the resistivity of the soil?

Each of the criteria is discussed with respect to how they are to be used and under what circumstances they are to be applied. The -0.85 volt criterion is usually applied to

coated pipes, and the potential shift criteria are usually used on bare pipes. Although the soil IR drop is usually negligible on well-coated pipes, it is a major factor in pipe-to-soil potential measurements on bare pipe. Therefore, when using the -0.85 volt or the 300 millivolt negative shift criterion on bare pipe, "careful consideration must be given to soil resistivity and the distance between the pipe and the reference electrode. Because of the uncertainties introduced by the effects of IR drop, more consideration should be given to the use of the 100 millivolt polarization shift as a criterion for bare pipe."

In considering IR drop, there is discussion concerning the effect of soil resistivity and the distance from the pipe to the reference electrode. It notes that the IR drop is of greater concern in soils of higher resistivity. It also points out that the depth of pipe must be known in determining the distance between the pipe and the reference electrode. Thus, areas which may appear to have a lower potential may in fact be a result of the pipe being at a shallower depth.

In discussion concerning the interval between measurements and the number of readings to be taken, it is noted that just because there are protective values at two given points does not necessarily mean that all the values between those points are at a protective level. This can be a problem especially on coated lines. It is possible that readings taken a mile apart on a coated pipe may indicate protection, yet there may be considerable coating damage between those readings; that damage would depress the potentials in the immediate vicinity, but would not substantially depress the potentials at the test stations. If this condition is suspected, it may be necessary to take measurements at very closely-spaced intervals (less than 5 feet) to determine the locations where the coating is damaged and where the potential indicates an inadequate level of protection.

18. A STUDY OF PROTECTIVE CRITERIA ON A PIPE SECTION IN A UNIFORM ENVIRONMENT. L.P. Sudrabin. Corrosion, February 1956, Vol. 12, No. 2, Page 16.

The meaning of pipe-to-soil potential measurement on a cathodically protected pipeline is dependent on the location of the reference electrode in relation to that pipeline. An experimental program is described to demonstrate the relationship of the reference electrode under freely corroding and under cathodically protected conditions. In the experiments, pipe section models were fabricated with known anodic areas established on an iron pipe. These anodic areas were high-purity zinc plates; the corrosion currents were measured between these established anodic areas and the iron pipe.

It was found that it was permissible to move the reference electrode farther away from the pipeline as the length of the corrosion current flow increased. However, it was also found that the potential gradients resulting from small local corrosion cells were not discernible by surface potential measurement.

Thus, the following generalizations with regard to reference electrode position for establishing the effectiveness of cathodic protection on bare pipe are:

- 1 Long-line corrosion currents are controlled when the protective potential (-0.85 volt) is measured to a copper-copper sulfate reference electrode in a remote location (100 feet away or further from the pipeline).

- 2 Long-line and intermediate corrosion currents are controlled when the protective potential is measured to a reference electrode placed over the pipeline. Local cell corrosion currents are reduced.

3 Long line, intermediate, and local cell corrosion currents are controlled when the protective potential is measured close to the pipe surface.

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